

***Spitzer* Observations of High Redshift Radio Galaxies**

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Abstract. We present the results of a comprehensive *Spitzer* survey of 70 radio galaxies across $1 < z < 5.2$. Using IRAC ($3.6 - 8.0 \mu\text{m}$), IRS ($16 \mu\text{m}$) and MIPS ($24 - 160 \mu\text{m}$) imaging, we decompose the rest-frame optical to infrared spectral energy distributions into stellar, AGN, and dust components and determine the contribution of host galaxy stellar emission at rest-frame $1.6 \mu\text{m}$ (*H*-band). The resultant stellar luminosities imply stellar masses of $10^{11-12} M_{\odot}$, independent of redshift, indicating that radio galaxies form early and are amongst the most massive galaxies observed over this redshift range. These powerful radio galaxies tend to lie in a similar region of mid-IR color-color space as unobscured AGN, despite the inferred stellar contribution to their shorter-wavelength, mid-IR SEDs. The observed rest-frame mid-IR luminosities are typically above $10^{11} L_{\odot}$, similar to lower redshift AGN. As expected, these exceptionally high mid-IR luminosities are consistent with an obscured, highly-accreting AGN. A weak, but significant, correlation of stellar mass with radio luminosity is found, consistent with earlier results.

1. Introduction

Luminous radio galaxies were the first class of obscured, or *type 2*, quasars to be discovered and characterized. They have accreting super-massive black holes whose continuum emission at UV, optical, and soft X-ray energies is absorbed by dust, thus largely giving them the appearance of *normal* galaxies at these wavelengths. More recently, hard X-ray and mid-IR surveys have identified the radio-quiet cousins to luminous radio galaxies (e.g. Norman et al. 2002; Stern et al. 2002; Martínez-Sansigre et al. 2005; Polletta et al. 2006; Lacy et al. 2007, in preparation). The main evidence that radio galaxies host super-massive black holes comes from the high luminosities of their radio lobes, which are fed by radio jets originating at the host galactic nuclei. The lobe spatial extents (up to a few Mpc, Saripalli et al. 2005) and luminosities ($L_{1.4\text{GHz}} \geq 10^{25} \text{ W Hz}^{-1}$) clearly

rule out a stellar origin for their energetics (e.g. Rees 1978). In terms of the orientation unification scheme for AGN (e.g. Antonucci 1993), radio galaxies are radio-loud quasars seen from an angle where an optically-thick torus obscures emission from the region closest to the central engine.

Across cosmic time, the host galaxies of these powerful radio sources appear to be uniquely robust indicators of the most massive galaxies in the universe. The most compelling evidence of this association of HzRGs with the most massive systems, however, is the tight correlation of the observed near-infrared Hubble, or $K - z$, diagram for powerful radio sources (e.g., Lilly & Longair 1984; Best et al. 1998; Eales et al. 1997; van Breugel et al. 1998; Jarvis et al. 2001; De Breuck et al. 2002; Willott et al. 2003; Rocca-Volmerange et al. 2004; Brookes et al. 2006): HzRGs form a narrow redshift sequence which traces the envelope of radio-quiet galaxies and is well modeled by the evolution of a stellar population formed at high redshift from an accumulation of up to $10^{12} M_{\odot}$ of pre-galactic material. The large-scale, double-lobed radio morphologies and enormous radio luminosities suggested early on that HzRGs must have spinning super-massive black holes powering relativistic jets in their centers (Rees 1978; Blandford & Payne 1982). With the more recent discovery that the stellar bulge and central black hole masses of galaxies are closely correlated (e.g. Tremaine et al. 2002), it is no longer a surprise that the parent galaxies of the most powerful radio sources occupy the upper end of the galaxy mass function.

Despite two decades of study since the initial discovery of the HzRG $K - z$ relation (Lilly & Longair 1984), the nature and tightness of the relation remains mysterious. The scatter in the relation is surprisingly low out to $z \sim 1$ and only increases modestly at higher redshifts as the observed K -band samples rest-frame optical emission (e.g. De Breuck et al. 2002). Interpretations have generally relied on these observed near-IR observations probing the stellar populations of the distant radio galaxies (e.g. Rocca-Volmerange et al. 2004). However, detailed interpretations have been complicated by (i) uncertain contributions of AGN-related light, (ii) evolution of the host galaxy stellar population(s), and (iii) band-shifting, meaning that observed $2.2 \mu\text{m}$ samples very different emitting wavelengths for different redshift sources, reaching into the rest-frame ultraviolet for the most distant HzRGs.

In these proceedings, we present observations of a large sample of HzRGs obtained with the *Spitzer Space Telescope* (Werner et al. 2004). By observing the same *rest-frame* near- to mid-IR spectral range for sources over a large redshift range ($1 < z < 5.2$), we remove many of the complications which plagued previous studies. In particular, the $1.6 \mu\text{m}$ peak of the stellar emission provides a reasonably robust measure of the stellar mass for stellar populations with ages $\lesssim 1$ Gyr (Sawicki 2001). Observations at longer wavelengths allow us to determine the contribution of warm, AGN-heated dust emission to the rest-frame near-IR emission.

Throughout we assume a concordance model of universe expansion, $\Omega_M = 1 - \Omega_{\Lambda} = 0.3$, $\Omega_0 = 1$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The data presented here represents the full set of processed *Spitzer* data. The full list of 70 HzRGs is presented online: <http://spider.ipac.caltech.edu/staff/seymour/SHizRaGs.html>. The data will eventually be made public on this webpage page and will be described in Seymour et al. (2007, in preparation).

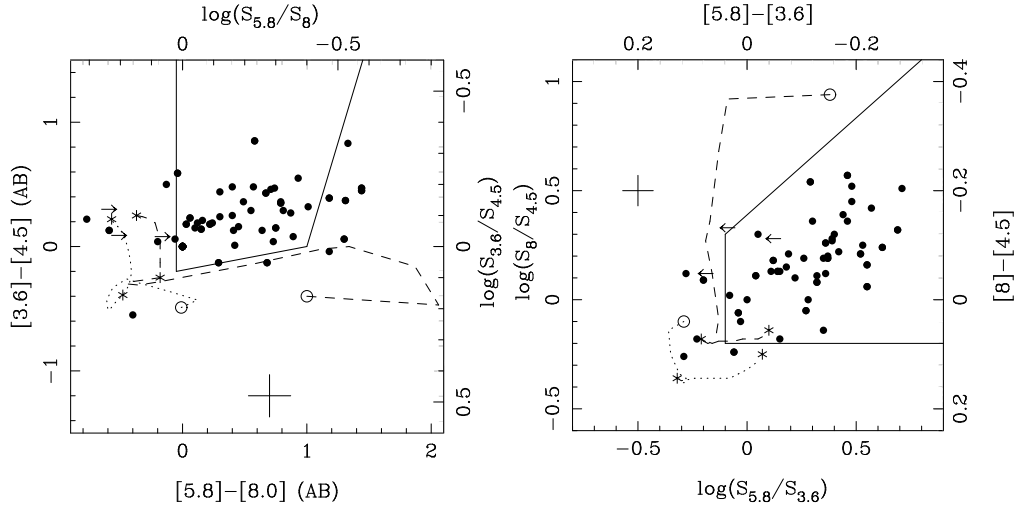


Figure 1. Mid-IR colors of HzRGs. Solid lines indicate empirical criteria that separate active galaxies (type 1) from Galactic stars and normal galaxies. The left-hand panel shows the criteria from Stern et al. (2005); the right-hand panel shows criteria from Lacy et al. (2004). Note that the axes have been selected to facilitate comparison with the original works. Crosses indicate typical uncertainties on the mid-IR photometry. HzRGs are the quintessential type 2, luminous AGN. As expected, they generally reside with the empirical AGN wedges. Tracks from redshift 0 to 2 for a late type star-burst galaxy (M82; dashed line), and an early type galaxy (NGC4429; dotted line) are included. These template SEDs are from Devriendt et al. (1999) and circles mark the $z = 0$ starting points and asterisks indicate $z = 1$ and $z = 2$ for the tracks. The tracks indicate that neither galaxy would be selected as an AGN candidate if located below $z = 2$.

2. Mid-IR Colors of HzRGs

Recent work has shown that IRAC mid-IR colors reliably isolate spectroscopically-confirmed, luminous, unobscured AGN (e.g. Lacy et al. 2004; Stern et al. 2005). However, since the surface density of sources with mid-IR colors similar to unobscured AGN is much higher than that of optically-selected (type 1) quasars, it has been inferred that obscured, type 2 quasars are likewise identifiable from their mid-IR colors. Due to their optical faintness, type 2 quasars are not as well studied as their bright, type 1 cousins. However, they are a natural consequence of AGN unification schemes (e.g. Antonucci 1993), and models of the hard X-ray background imply that they outnumber type 1 quasars by factors of several (e.g. Treister & Urry 2005).

Our *Spitzer* HzRG sample represents the largest sample of confirmed type 2 quasars with IRAC photometry obtained to date. Fig. 1 presents the measured mid-IR colors of the subsample with detections in all four IRAC bands on the color-color plots of Lacy et al. (2004) and Stern et al. (2005). As expected, the HzRG sample tends to fall within the AGN wedges identified in each of these diagrams.

3. Stellar, Dust and AGN Models

We model the radio galaxy IR SEDs with a four component model comprised of an elliptical galaxy Composite Stellar Population (CSP) template and three Black Bodies (BB) of different dust temperatures. Best-fit parameters for the models are determined using standard χ^2 minimization techniques. The uncertainties on the flux densities used to determine the χ^2 of a specific fit include both random (from the observations) and systematic (e.g. the detector zero points and the shape of the SED) uncertainties, which are added in quadrature. The full fitting is only done for sources with MIPS $24\mu\text{m}$ detections as we need both enough data points to fit our model and a detection longward of the IRAC bands to provide sufficient leverage on the dust component. For sources without MIPS detections or observations we do not have enough data points to do secure fitting of this model. Hence in many cases we only get an upper limit to the stellar component, though in some cases we can get a likely mass when the IRAC bands fit the stellar component well.

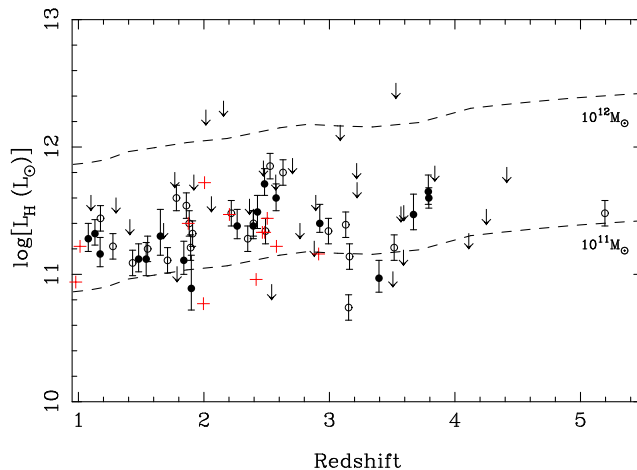


Figure 2. Rest-frame H -band stellar luminosity versus redshift for the *Spitzer* HzRG sample, derived from the best-fit models to the multi-band photometry. Solid circles indicate those luminosities derived from HzRGs with MIPS detections, whilst open circles are the luminosities derived from HzRGs without MIPS detections. Those radio galaxies where only a maximum fit of the stellar SED was possible have upper limits which are indicated by downward arrows. The dashed lines represent the luminosities of elliptical galaxies with $z_{\text{form}} = 10$ taken from the PÉGASE.2 models and normalized to $10^{11} M_{\odot}$ and $10^{12} M_{\odot}$. Crosses mark the luminosity of Sub-mm Galaxies from Borys et al. (2005) re-derived in the same fashion as our luminosities.

4. Rest-frame Near-IR Stellar Luminosities

The rest-frame H -band stellar luminosities are found mainly to lie in the $10^{11} - 10^{12} L_{\odot}$ range, as illustrated in Fig. 2. Overlaid are PÉGASE.2 models illustrating the luminosity of an elliptical galaxy with $z_{\text{form}} = 10$ for masses of 10^{11} to $10^{12} M_{\odot}$. The derived HzRG stellar luminosities are consistent with extremely

massive hosts, with masses of a few $\times 10^{11} M_{\odot}$ out to $z = 4$. Using the PÉGASE models used in Fig. 2 we are able to derive stellar masses. Systematic uncertainties of this choice are discussed at length in Seymour et al. (2007, in preparation).

5. Radio Power Dependence on Stellar Mass

Fig. 3 presents the derived stellar masses plotted against rest-frame 3 GHz radio luminosity. A weak correlation is visually apparent, though a proper statistical survival analysis that accounts for the multiple upper-limits finds that the Cox Hazard Probability is only 0.5. This means that there is only a 50% chance that stellar mass correlates with radio luminosity for our sample. The detection of a correlation, showing that more powerful radio sources are hosted by more massive galaxies, would not be surprising, and is in fact expected if the $M - \sigma$ relation holds to high redshift. Previous work, inferring stellar masses from the *observed* near-IR flux rather than the *rest-frame* near-IR luminosity, has suggested this correlation in the past (Eales et al. 1997; Best et al. 1998; De Breuck et al. 2002; Willott et al. 2003).

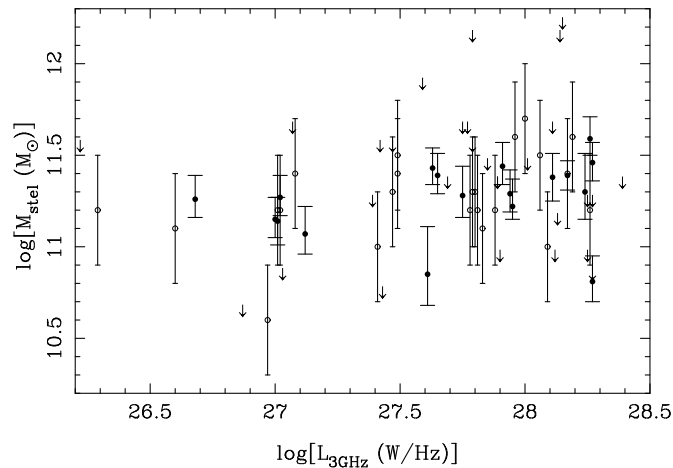


Figure 3. Stellar mass against rest-frame 3 GHz luminosity. There is evidence of a slight trend, such that the most massive galaxies host more powerful radio sources, though, accounting for the large number of upper limits in the plot, a formal survival analysis shows only a 50% chance of the two observables being correlated. Deeper data and better coverage with the longer wavelength *Spitzer* cameras would show conclusively whether or not this correlation exists.

6. Conclusions

We have performed a comprehensive infrared survey of 70 HzRGs above $z = 1$, the first time such galaxies have been detected in the rest-frame near-IR and mid-IR. This work presents the largest sample of confirmed type 2 quasars to be systematically studied with *Spitzer*. As expected, they mostly lie the IRAC

color-color space dominated by type 1 AGN found empirically by Lacy et al. (2004) and Stern et al. (2005) and theoretically by Sajina et al. (2005).

We fit composite stellar and dust models to obtain stellar near-IR luminosities and stellar masses. The stellar masses average $10^{11.4} M_{\odot}$ across $z = 1 - 4$. We also find a slight trend that the galaxies with the higher stellar masses host the more powerful radio sources, though a full survival analysis taking proper account of upper limits finds this correlation has only a 50% of being correct. The correlation is expected if the $M - \sigma$ relation holds to high redshift.

Acknowledgments. We would like to thank Jose Afonso and the LOC for organising a timely, interesting and thoroughly enjoyable meeting. We'd also like to thank Asher Stern for his sterling work so far on the project.

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